In-Situ Mosaic Production at JPL/MIPL

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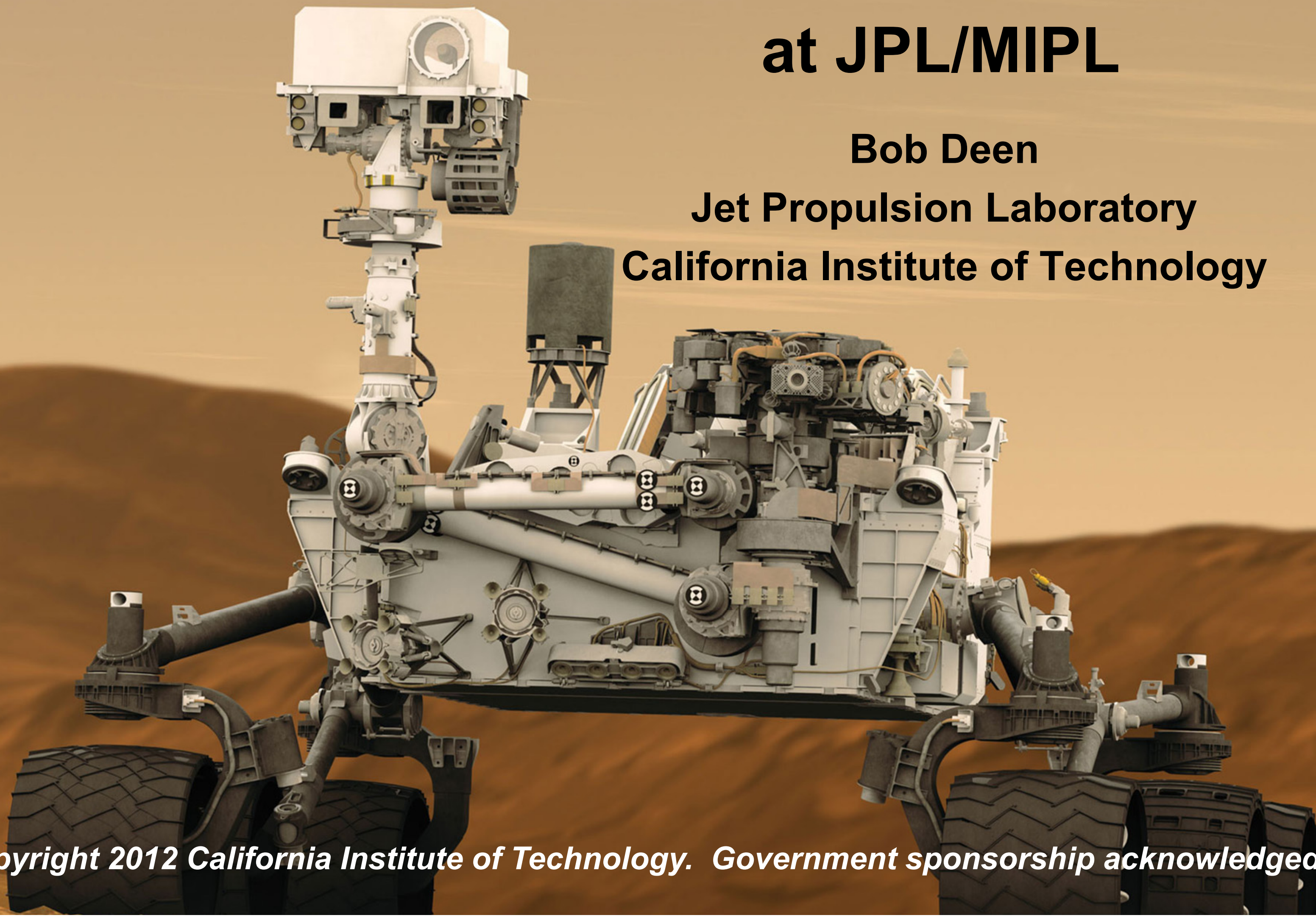


Introduction

- **Multimission Image Processing Lab (MIPL) at JPL is responsible for (among other things) the ground-based operational image processing of all the recent in-situ Mars missions**
  - Mars Pathfinder
  - Mars Polar Lander
  - Mars Exploration Rovers (MER)
  - Phoenix
  - Mars Science Lab (MSL)
- **Mosaics are probably the most visible products from MIPL**
  - Generated for virtually every rover position at which a panorama is taken
  - Provide better environmental context than single images
    - Valuable to operations and science personnel
  - Arguably the signature products for public engagement

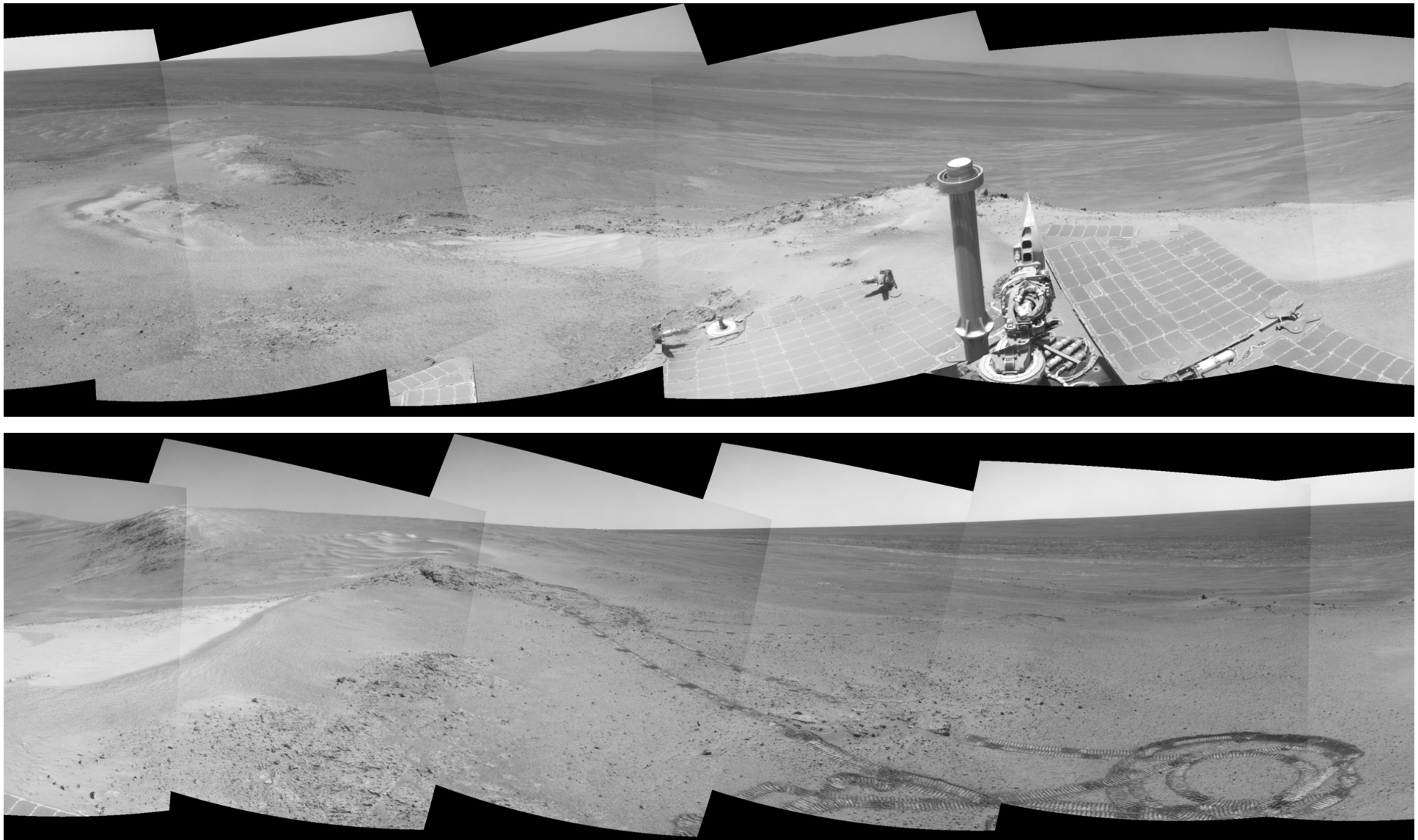
Mosaic Fundamentals

- **A mosaic is a single larger image that is made by combining many individual smaller frames.**
  - The trick is, to transform and match the images so they look like a unified whole.
- **Requirements**
  - Images have calibrated camera model
    - Transforms XYZ world coordinates to line,sample image coordinates
  - Pointing of each image is known
    - Telemetry from camera mount (e.g. pan/tilt unit)
    - Pointing can be adjusted to reduce seams
  - Traceability of each pixel to source image must be maintained
    - Maintains scientific integrity – quantitative measurements are possible
    - No unconstrained warping
    - No seam blending

MIPL-Supported Projections

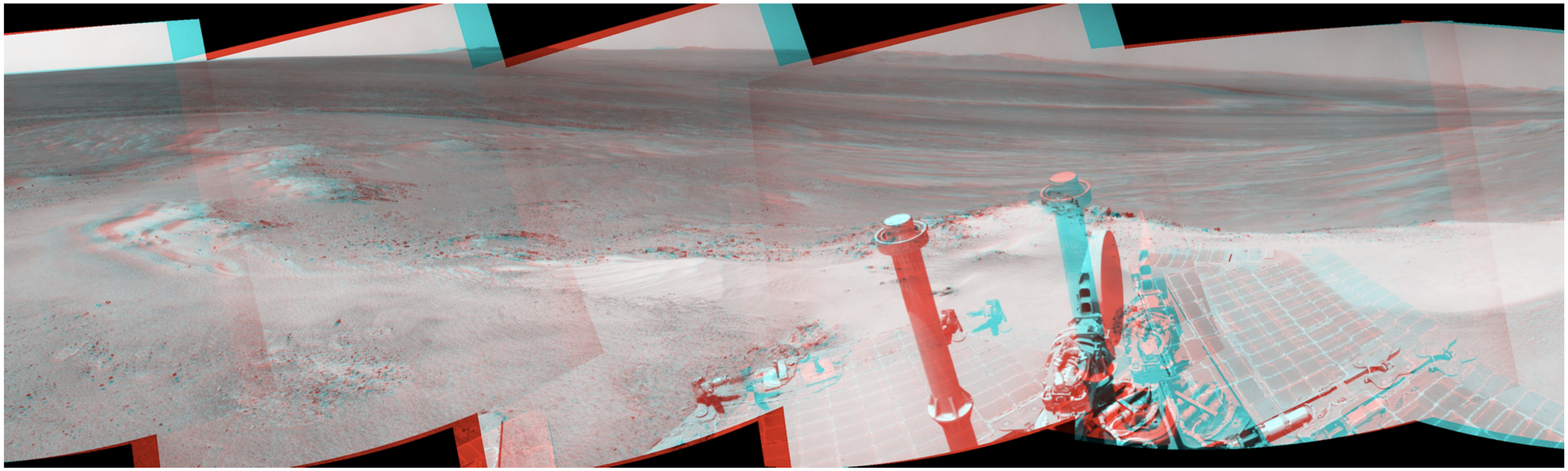
- **Cylindrical**
  - Rows are constant lines of elevation, columns constant azimuth
  - Single point of view, generally the center of the ring described by the cameras
  - Standard mosaic for non-stereo in-situ views
- **Polar**
  - Elevation is distance from center (nadir); azimuth goes around the circle
  - Useful for nadir-to-horizon context.
- **Vertical**
  - Rows are lines of constant X, columns are constant Y
  - Overhead view
  - Suffers from severe layover effects when scene doesn't match surface model
- **Perspective**
  - Models a pinhole camera at a certain point of view
  - Most natural view for small mosaics
  - Can be stereo with appropriate POV
- **Cylindrical-Perspective Hybrid**
  - Each column has its own camera model from its own POV
  - Suitable for stereo panoramas
- **Orthorectified**
  - Uses XYZ data to create "true" overhead view
  - Prototype software

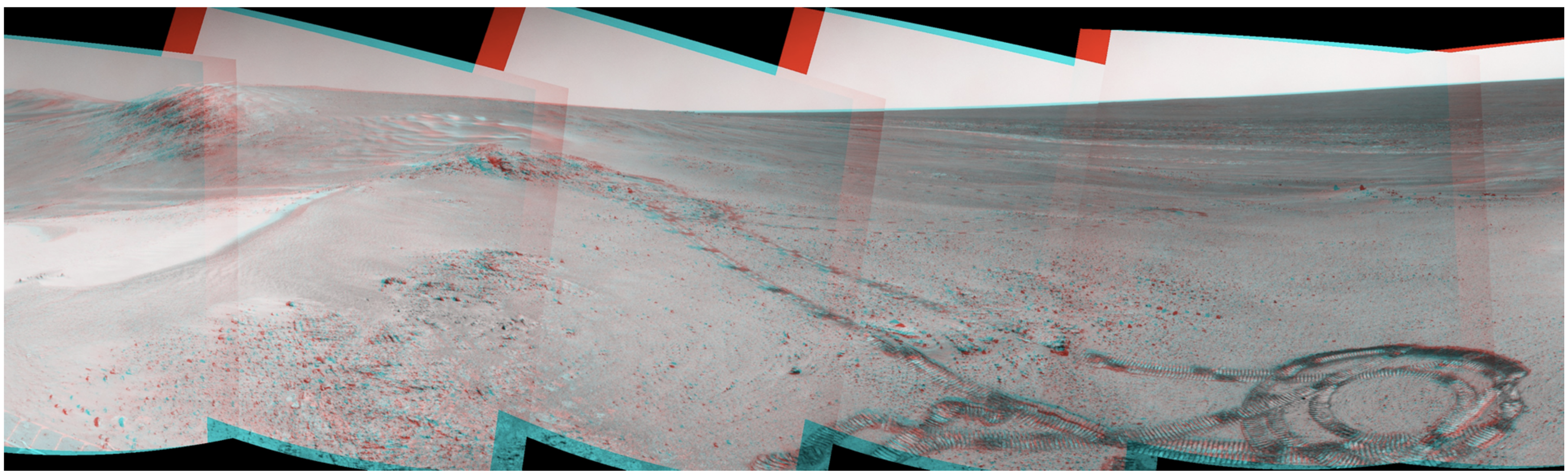
Cylindrical Projection



Opportunity Sol 2820 (Greeley Haven) Navcam, 180 degrees azimuth each

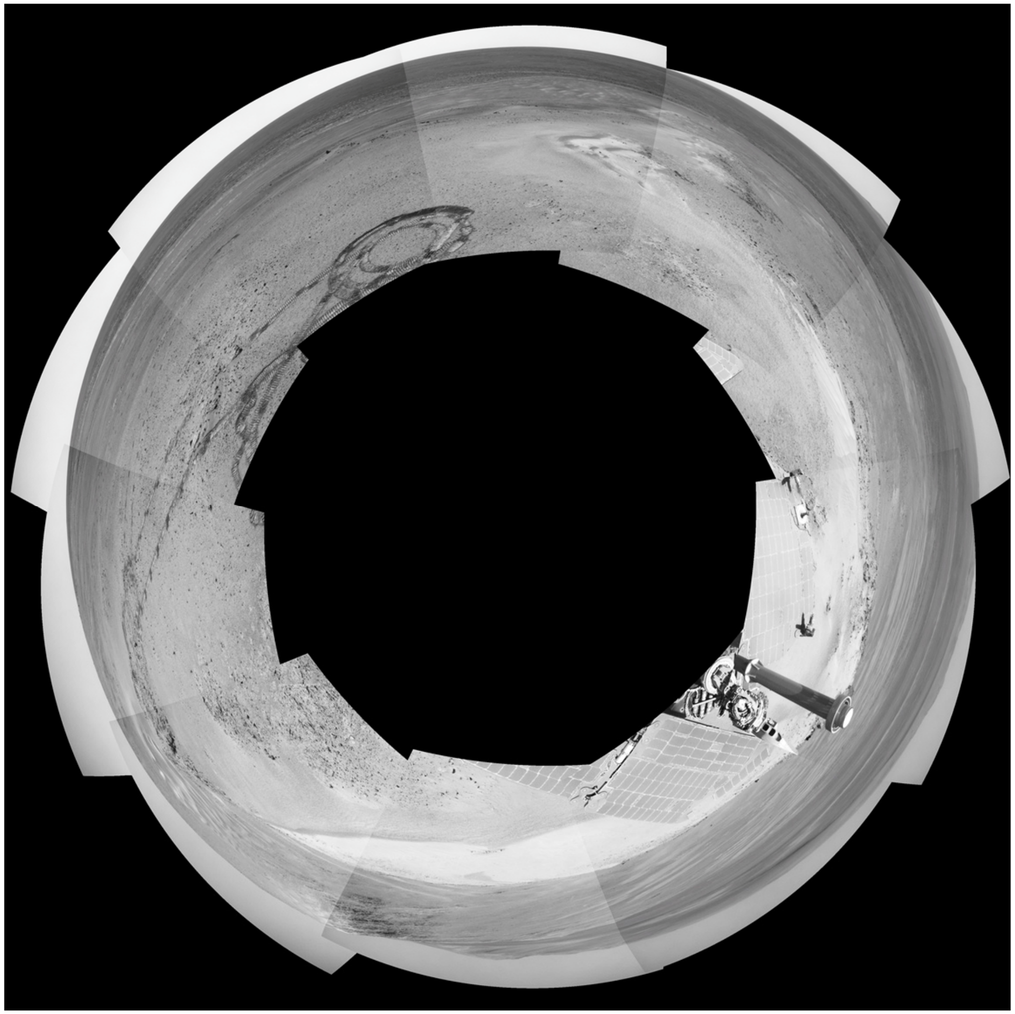
Cylindrical-Perspective Hybrid Projection





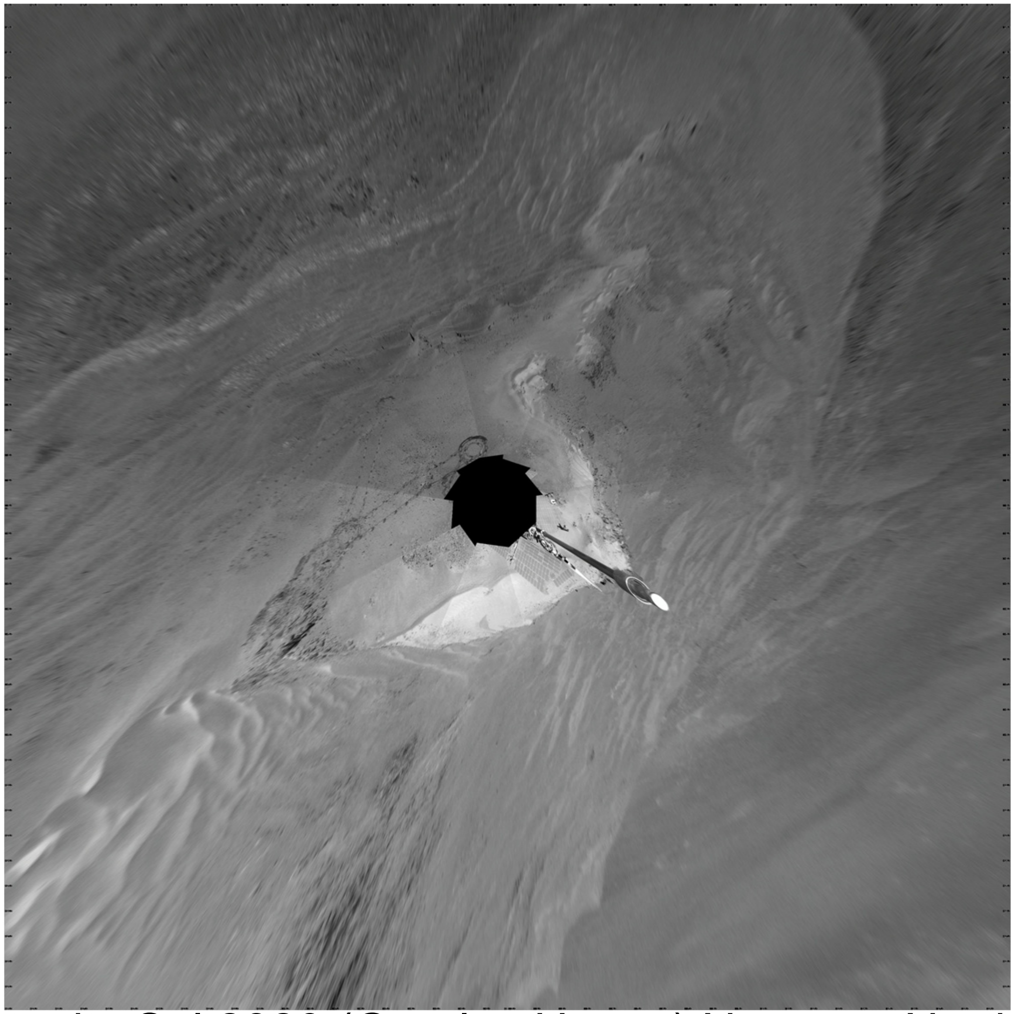
Opportunity Sol 2820 (Greeley Haven) Navcam, 180 degrees azimuth each

Polar Projection



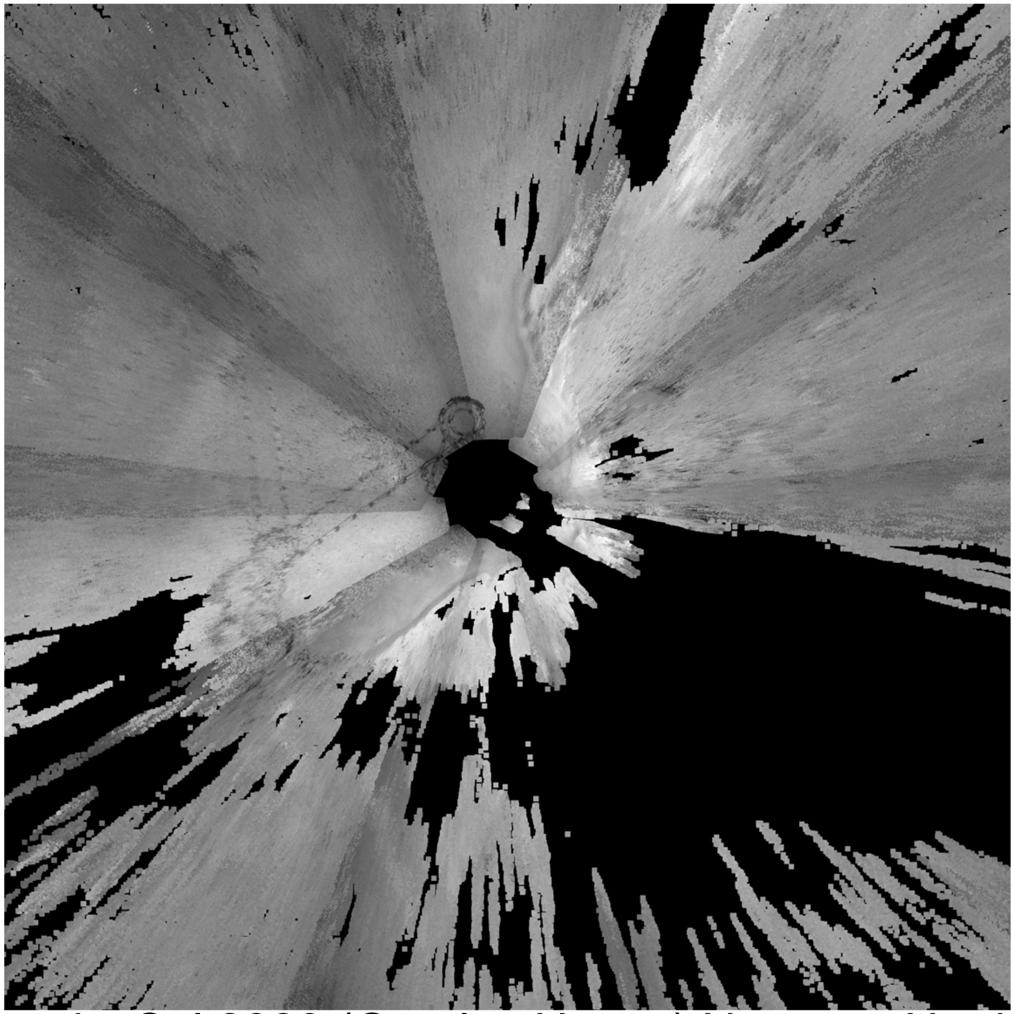
Opportunity Sol 2820 (Greeley Haven) Navcam, North is up

Vertical Projection



Opportunity Sol 2820 (Greeley Haven) Navcam, North is up

Orthorectified Projection



Opportunity Sol 2820 (Greeley Haven) Navcam, North is up

Perspective Projection

Opportunity Sol 2820 (Greeley Haven) Navcam

Mosaic Challenges

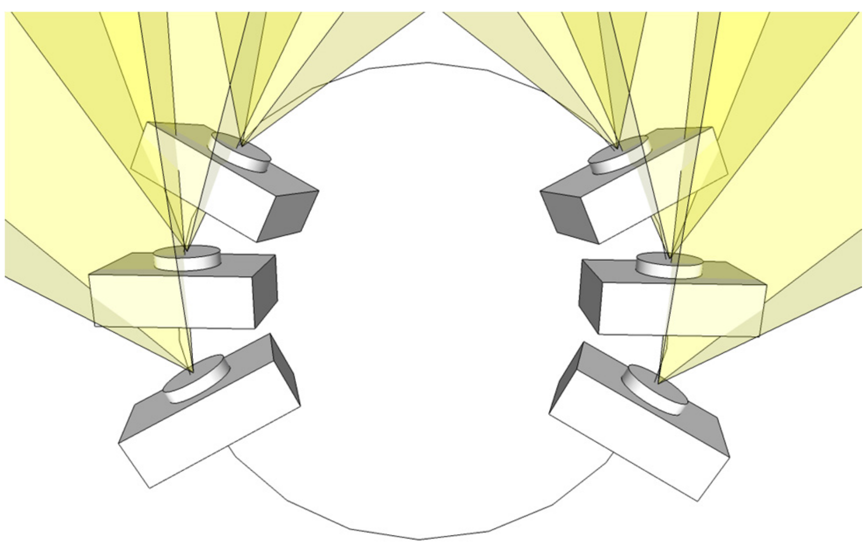
- **Parallax – the primary issue**
- **Imprecise pointing knowledge**
- **Radiometric errors**

What is Parallax

- **Parallax occurs when you view a 3-dimensional scene with different depths from two different points in space**
  - Hold your finger in front of your face, close eyes alternately – your finger “moves” with respect to the background.
- **Nearby objects have greater apparent motion than distant objects**
  - This is the fundamental basis of stereo vision
  - But causes problems for mosaics
- **Foreground objects hide different parts of the background in different views**
  - Called “occlusion”, this means some objects are visible in one image but not another
- **For near-field objects, different images may show different sides of the same object**

Source of Parallax for In-Situ Mosaics

- **Stereo camera heads for in-situ missions consist of cameras mounted to either side of a mast head**
- **This means that as the head is moved in azimuth, the cameras describe a circle**
- **Each frame is taken from a different position in space**
  - This creates parallax – imaging the scene from different points of view



Dealing with Parallax in Mosaics

- **Fundamental challenge of mosaics is to transform the images so they share a common point of view – that of the output projection**
- **This could be done perfectly if the camera pivoted about its entrance pupil**
  - Images naturally share the same point of view, so no transform is needed and there is no parallax
  - Impractical for stereo-vision cameras
    - A “flagpole” mounting could pivot one camera about its entrance pupil, but stereo partner would have twice as much parallax
- **Must project the images to accomplish this transform**

Projecting Images

- **Transforming the point of view means projecting the image back into 3-D space and then looking at the result from a different POV.**
- **If 3-D shape of the scene is known, the projection can be done exactly**
  - Basis of orthorectified projections
  - Objects are not distorted, but holes or gores appear in the image due to occlusions
  - Requires stereo analysis of terrain, but stereo not always available, and does not necessarily cover the entire mosaic
- **If 3-D shape is not known, an assumed shape – a surface model – must be used**
  - Project image to surface model, view from another point of view
  - Works well if surface model closely matches actual surface
    - Deviations from model cause distortions due to parallax
    - Parallax distortions are based on deviations from surface model, which are usually much less than parallax in the raw images.

Surface Model

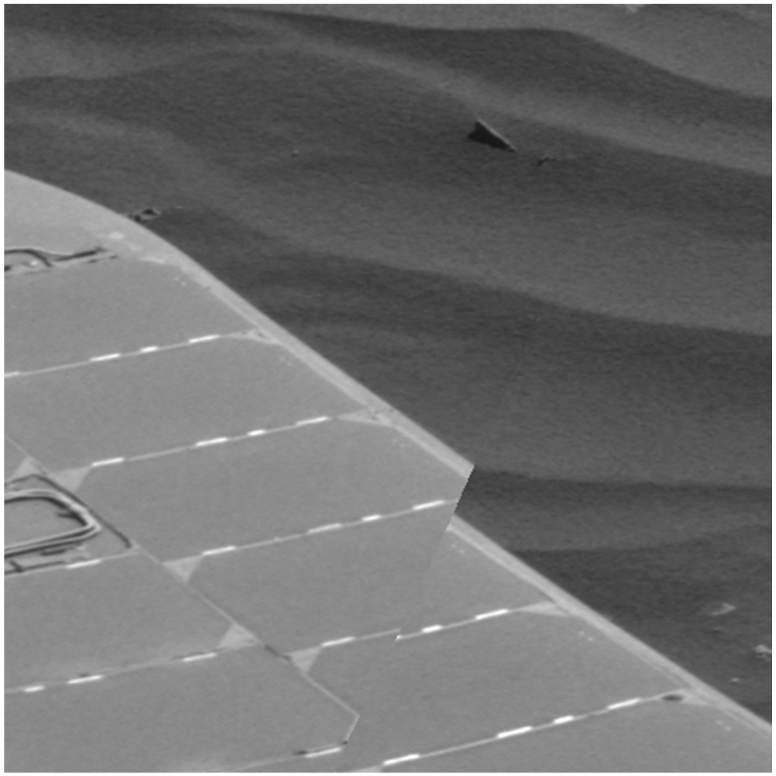
- **For in-situ work, a flat plane surface model works well**
  – Models most scenes
    - Notable exceptions being cliff faces and large nearby boulders
- **Tilted surface model works even better**
  – Allows overall topography near rover to be accounted for
- **Distant objects relatively unaffected by parallax or surface model deviations**

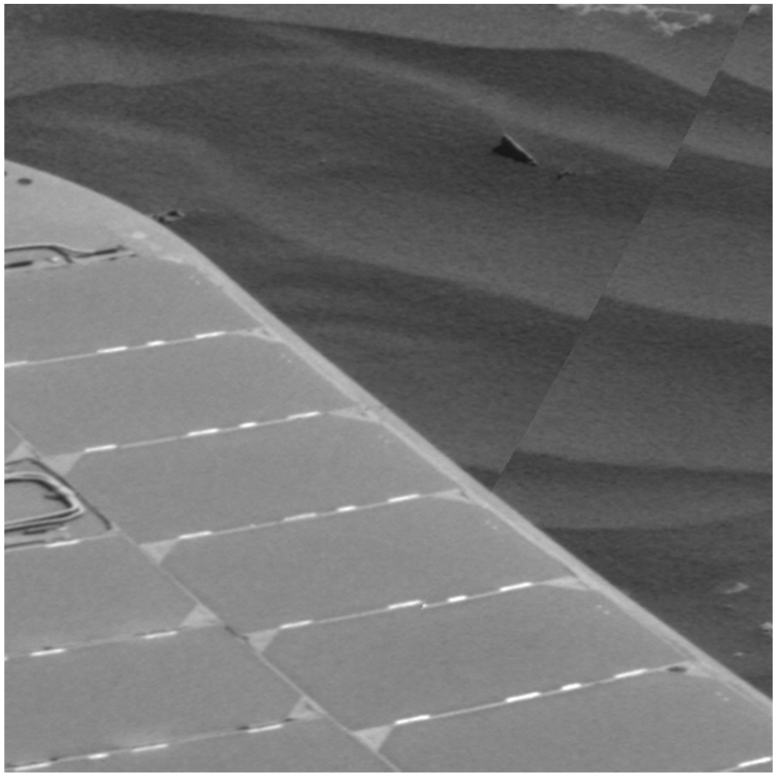
Parallax Artifacts

- **Perfect correction is not possible**
  - Orthorectified projection – geometry is correct but holes or gores appear due to occlusions. Seams can be perfect if XYZ data is.
  - Surface model-based projection – No holes, but deviations from surface model create distortion, evident as discontinuities at seams.
  - Image warping – Can provide illusion of no seams, but distortion of geometry leads to pretty pictures unsuitable for scientific interpretation.

Parallax Example

- **Surface model can be set to the ground, or the deck**
  - One will have seams, the other won't
  - Can't eliminate seams in both at once due to parallax
  - Example: Spirit pancams, McMurdo site. Difference is surface model



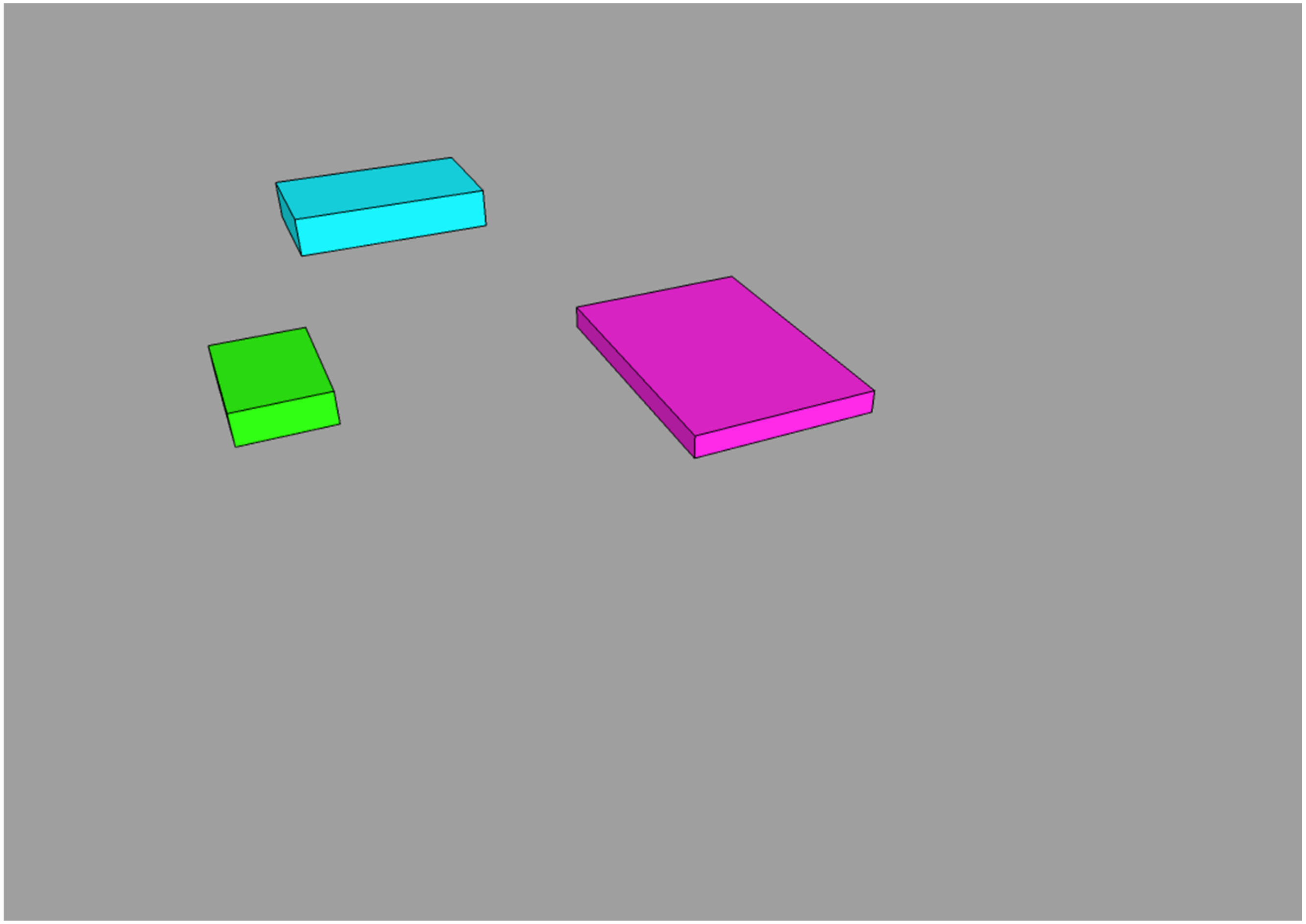


Mosaic Process

- **The next few slides go through the mosaic process graphically.**

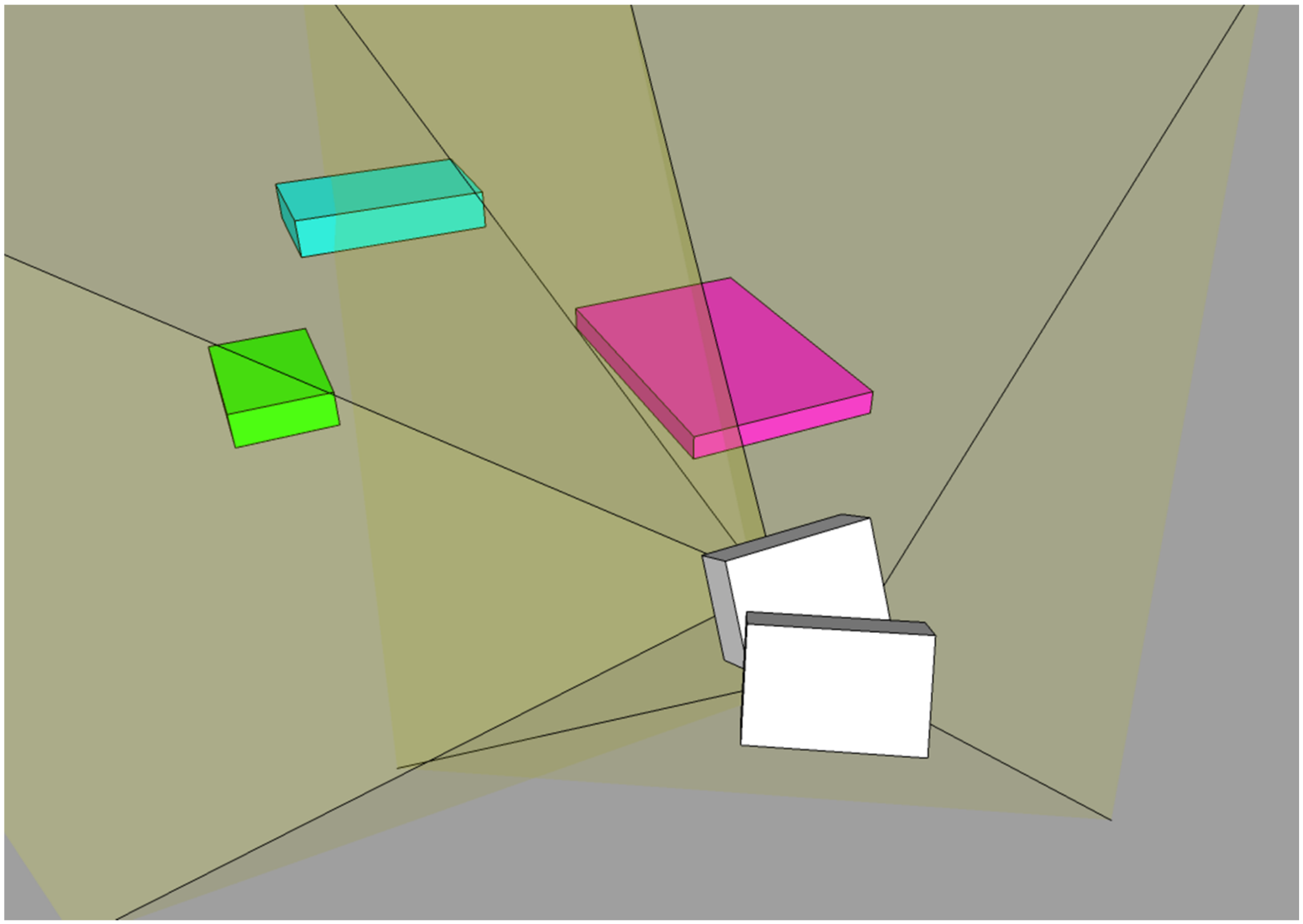
Mosaic Process

- **3D scene**



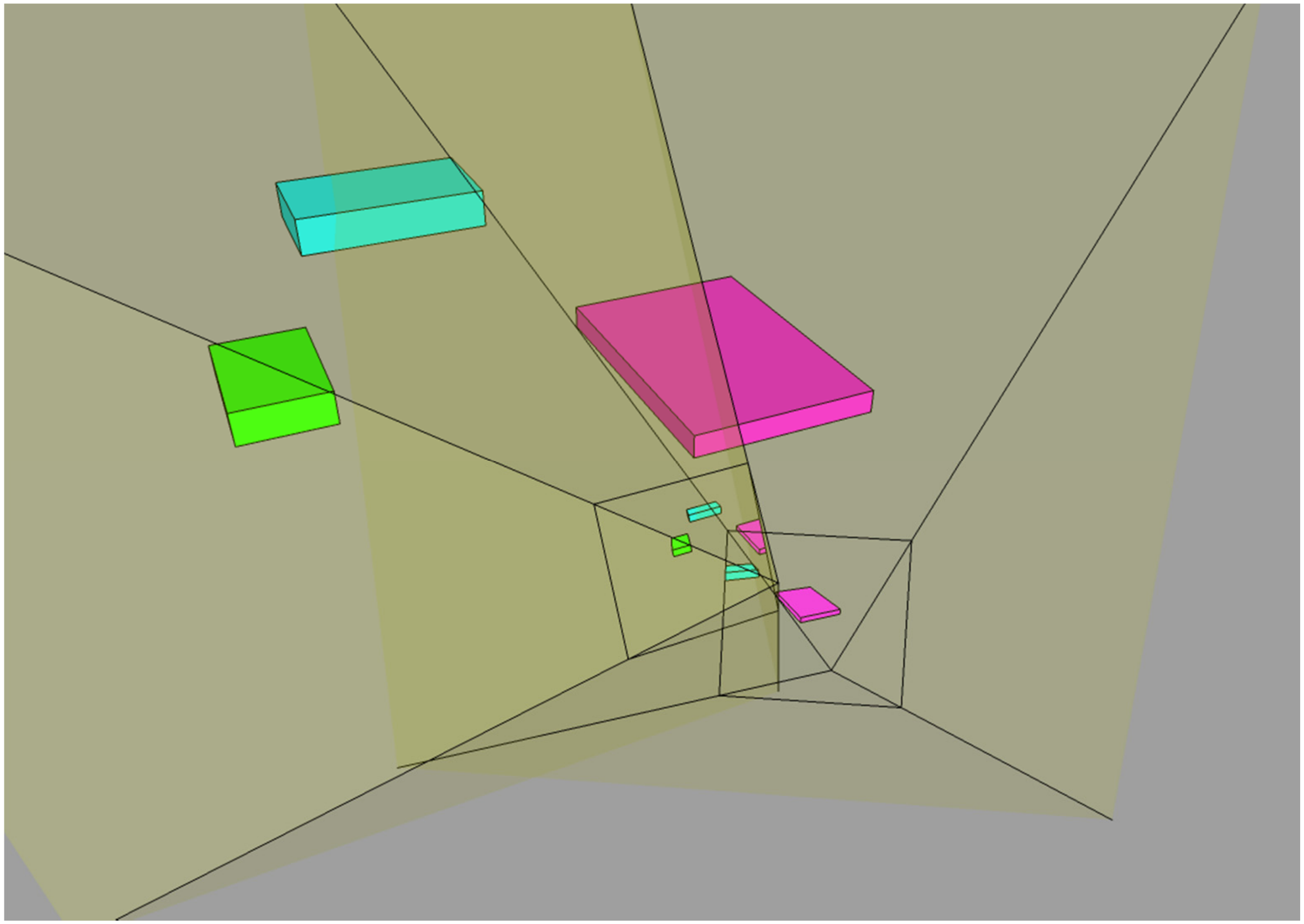
Mosaic Process

- **Cameras and overlapping fields of view**



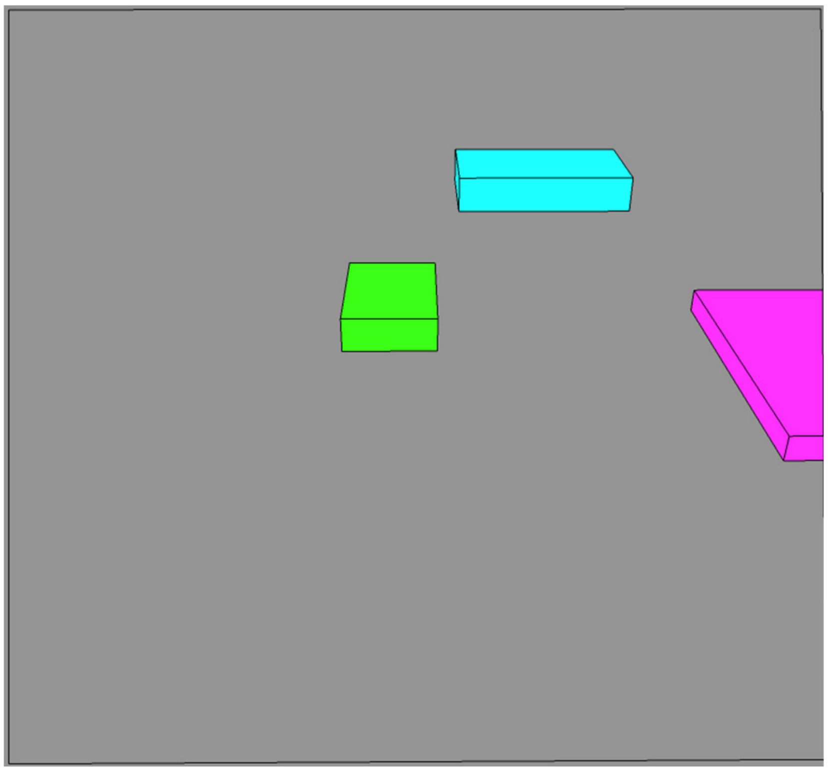
Mosaic Process

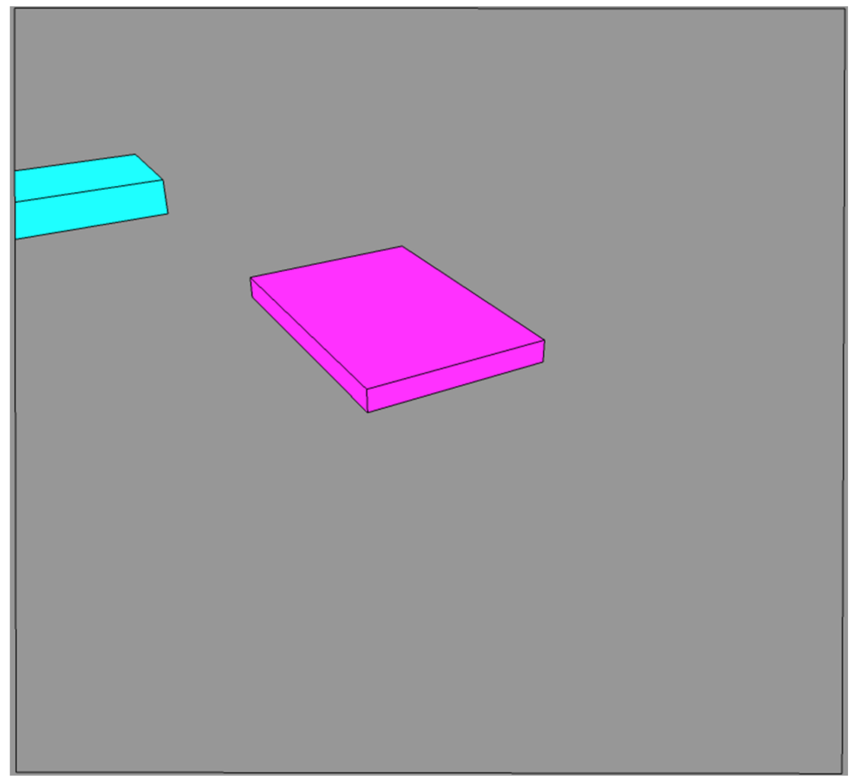
- **Resulting images in 3D space**



Mosaic Process

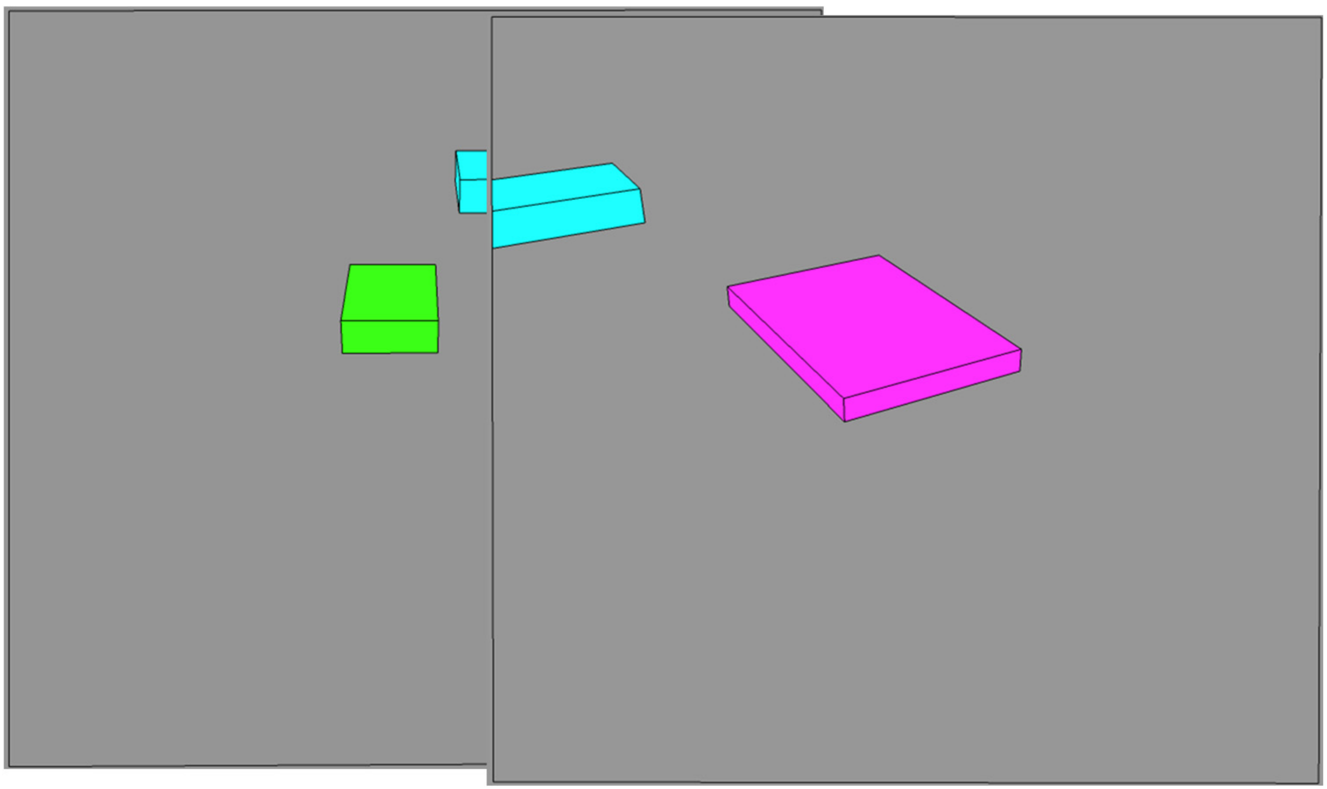
- **Resulting Images**





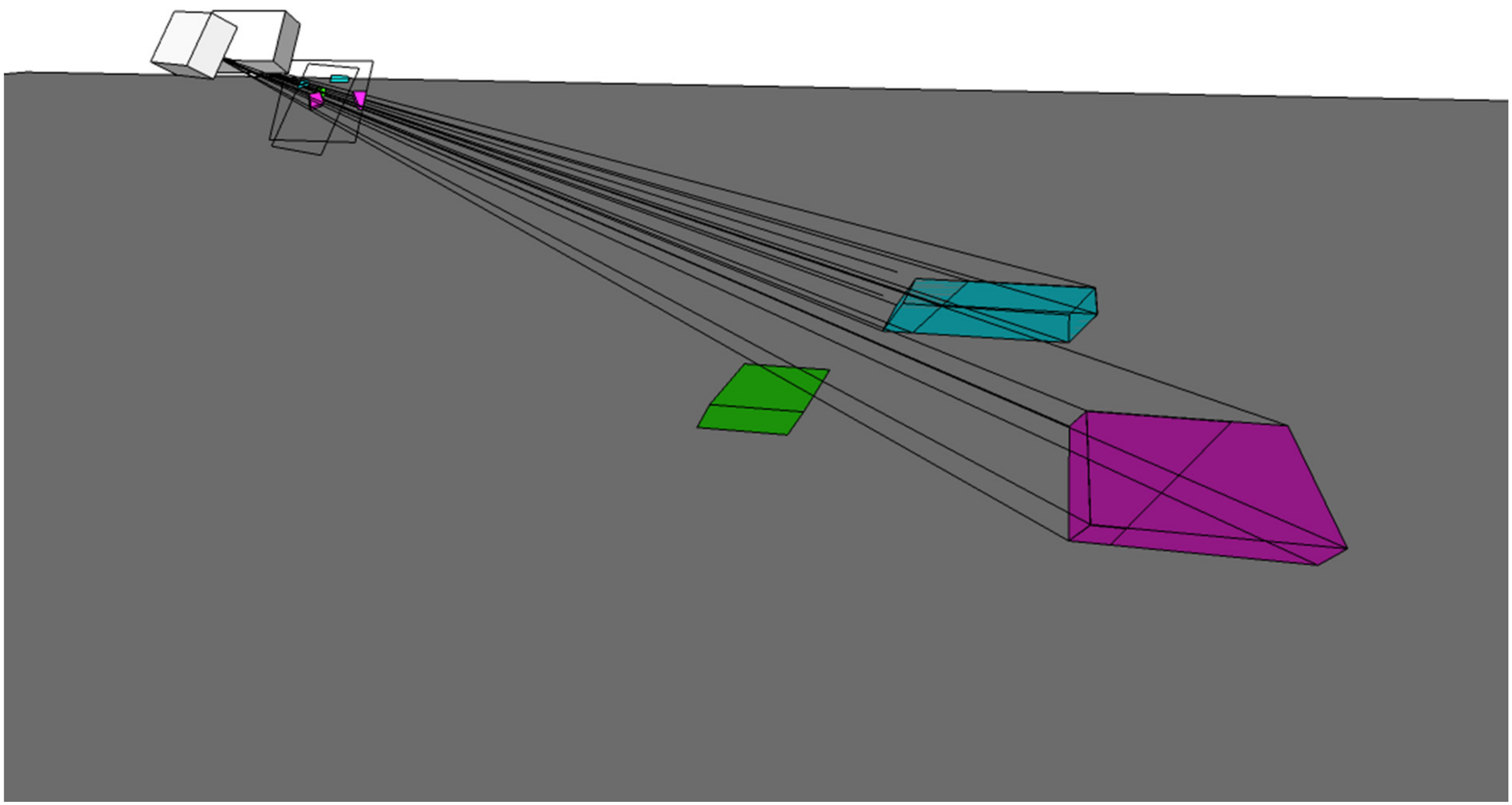
Mosaic Process

- **Naïve mosaic (no projection, huge parallax)**



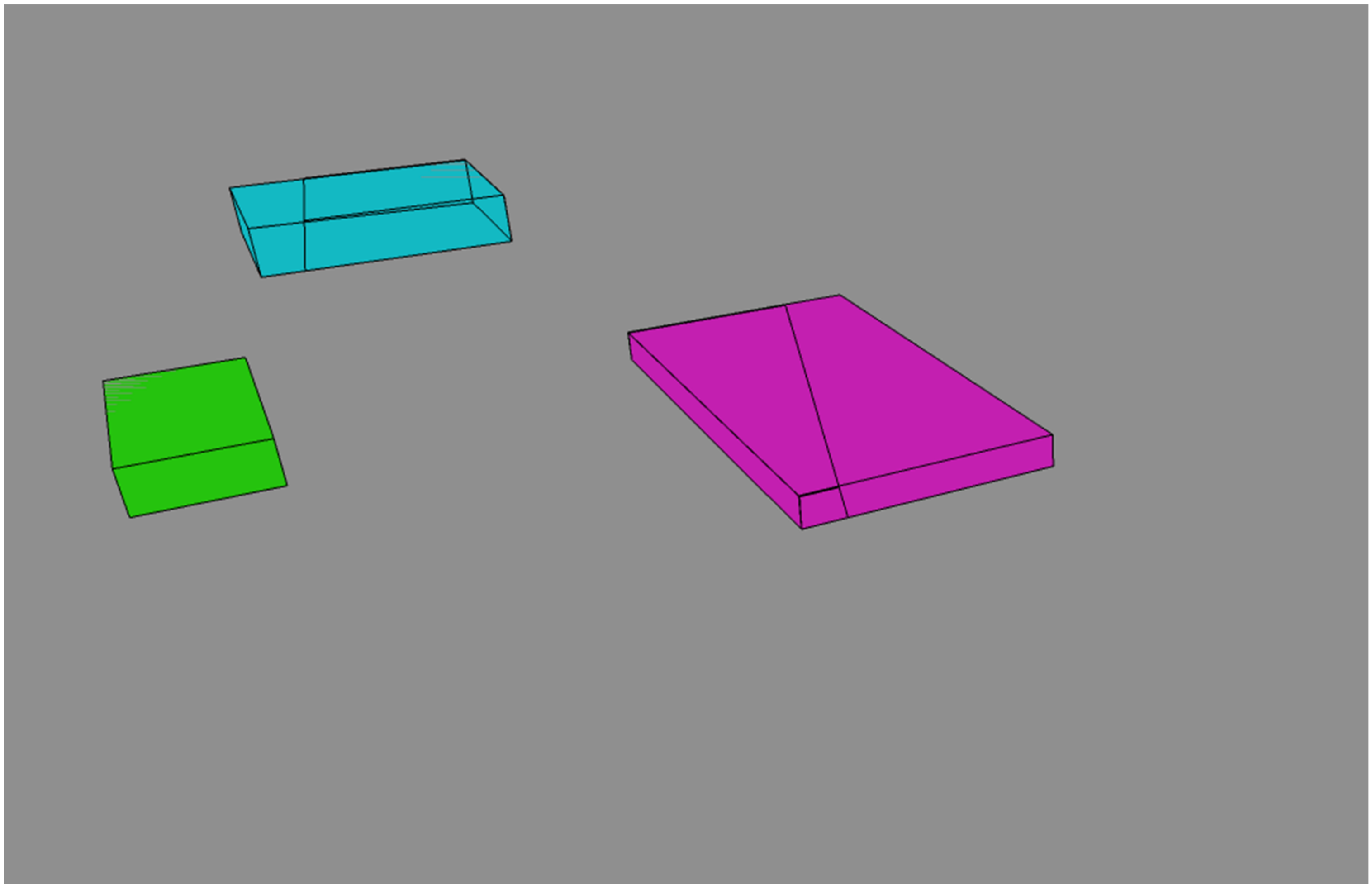
Mosaic Process

- **Project images down to surface model**



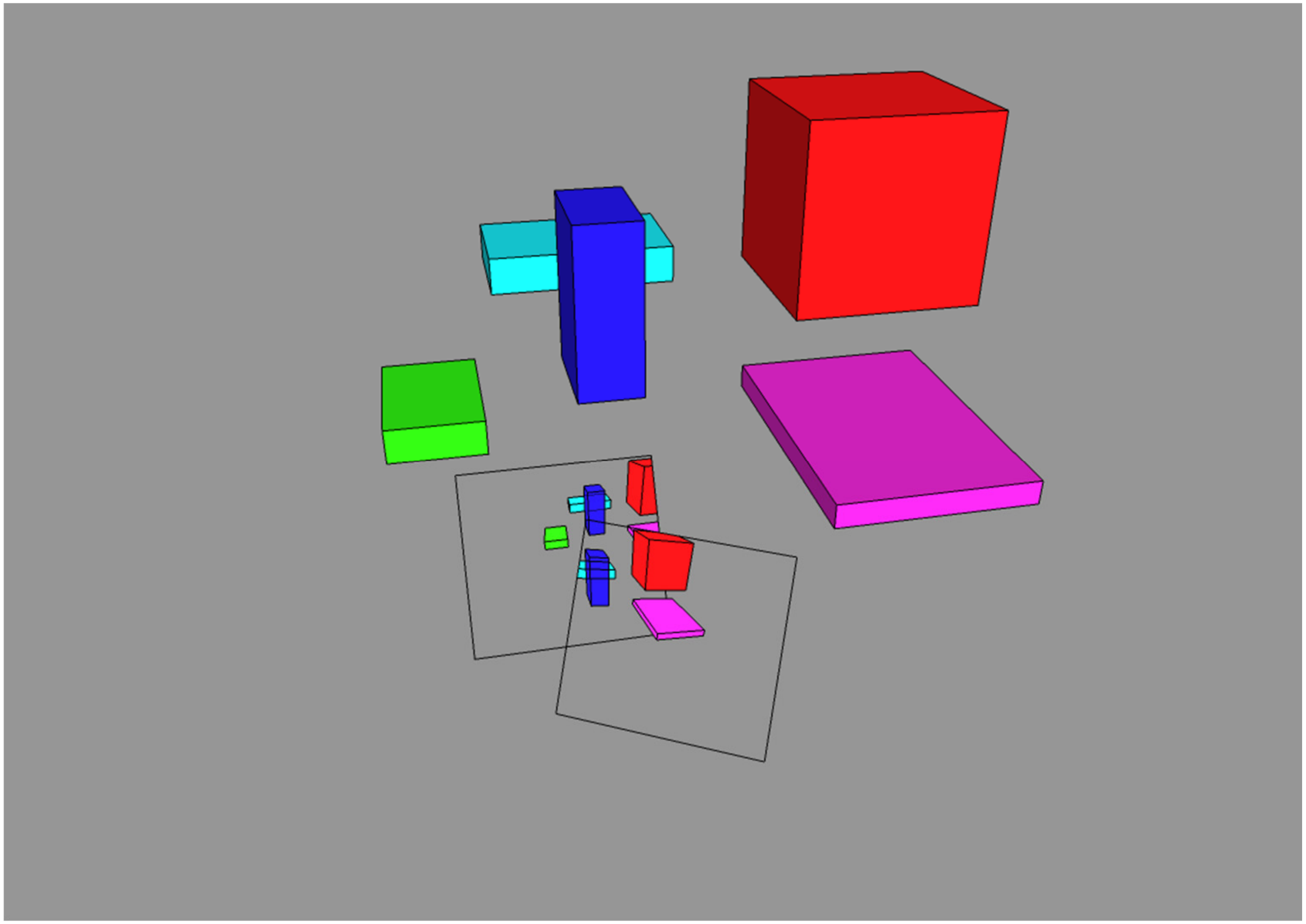
Mosaic Process

- **Mosaic from unified point of view**



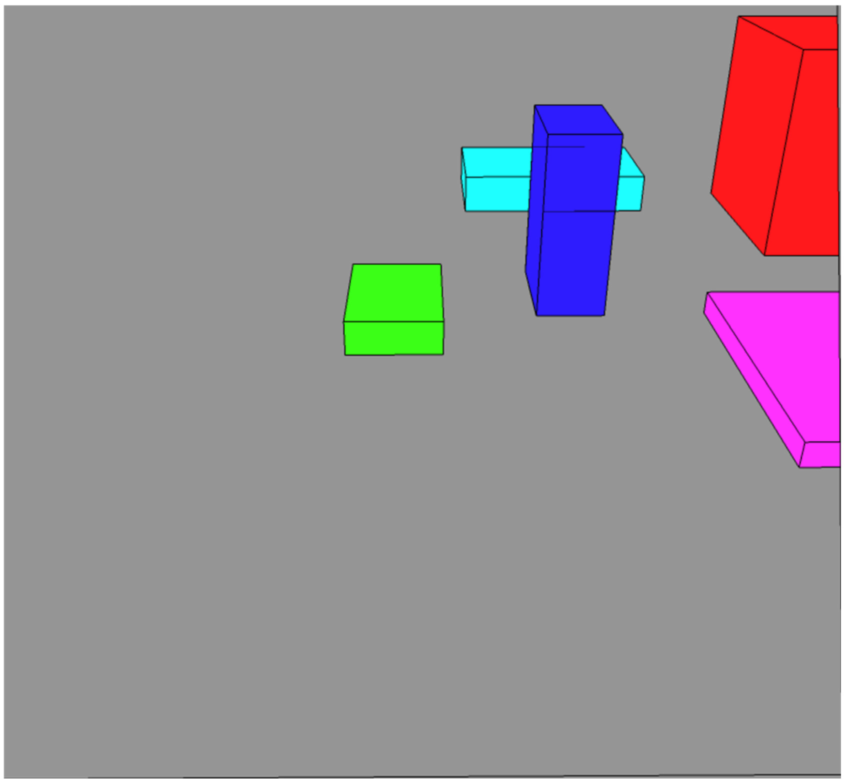
Mosaic Process – Parallax

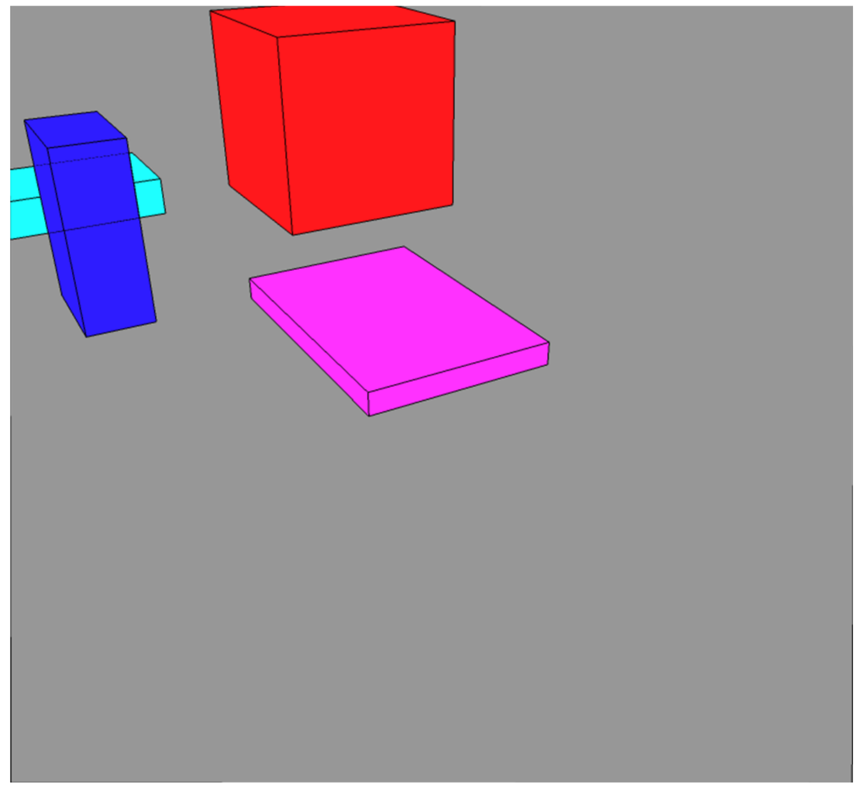
- **Add some tall objects to scene (do not match surface model well)**



Mosaic Process - Parallax

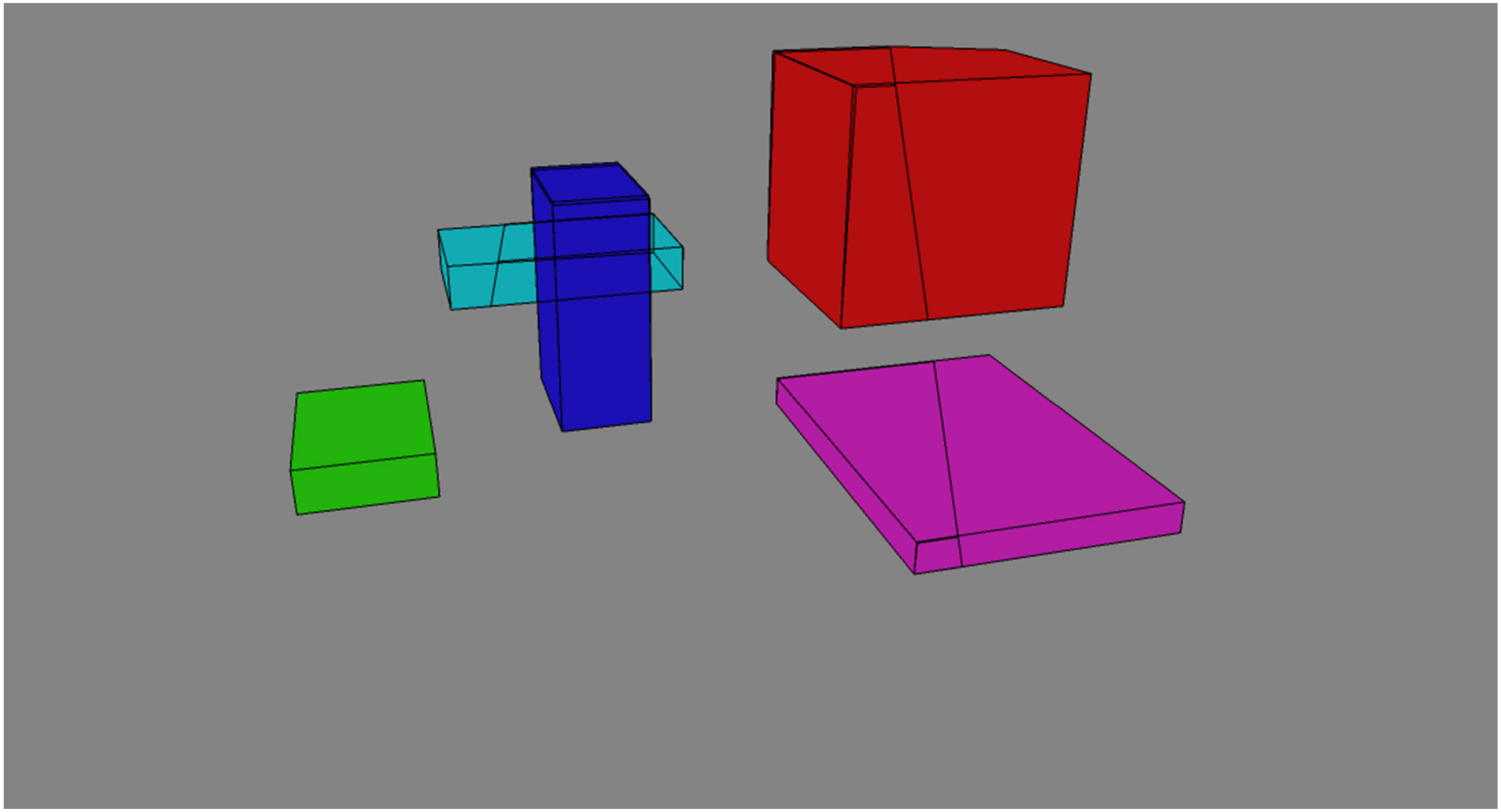
- **Resulting images**





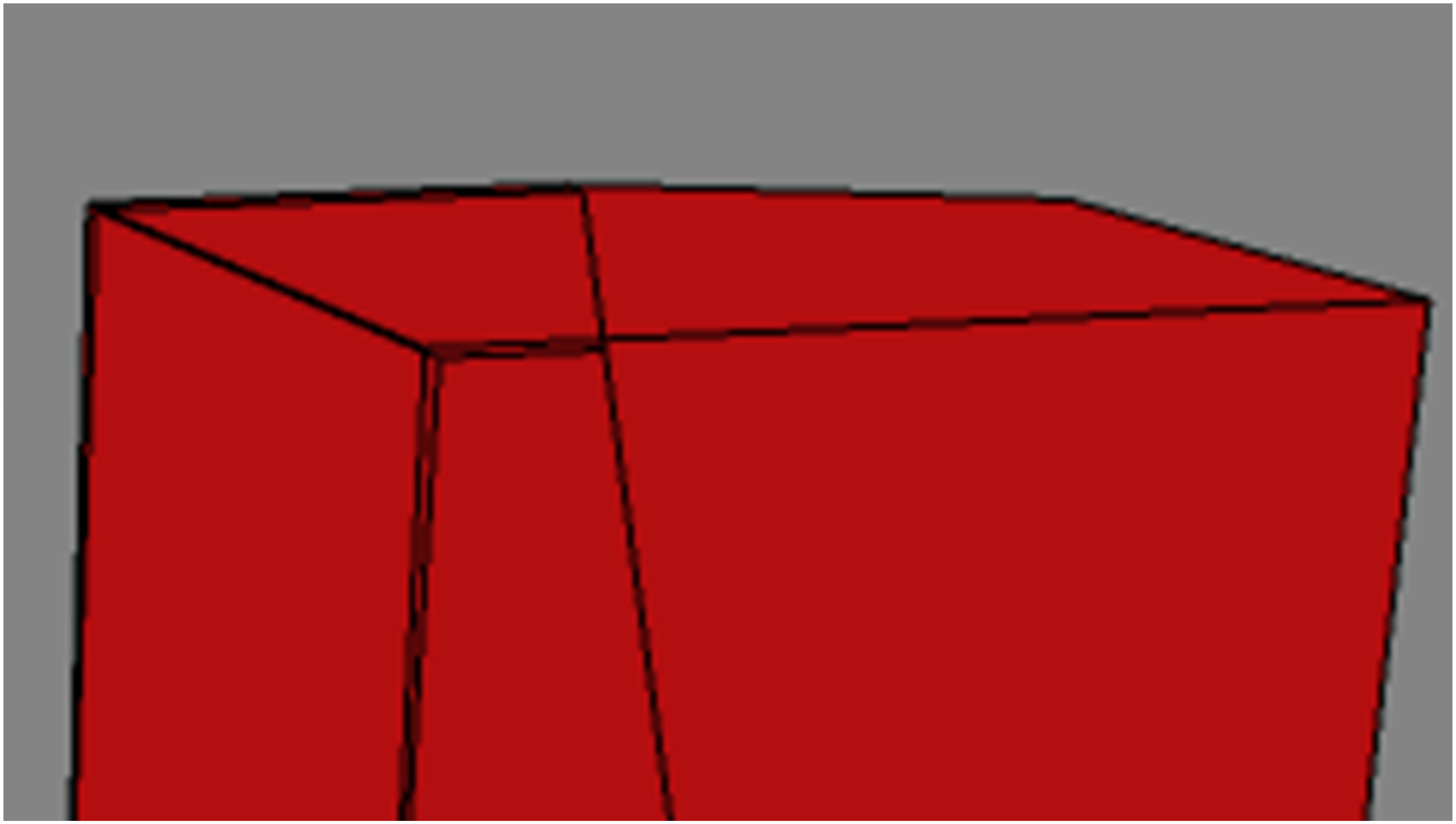
Mosaic Process - Parallax

- **Resulting Mosaic**



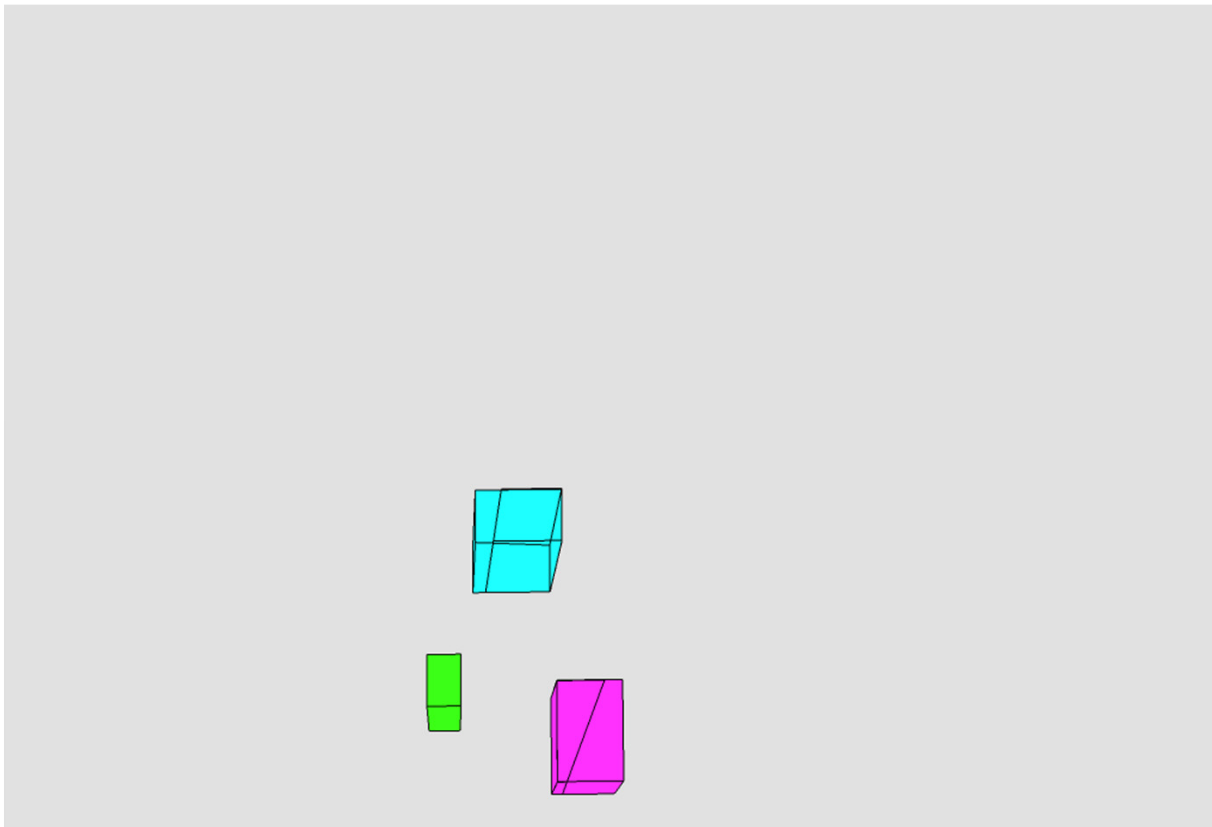
Mosaic Process – Parallax

- **Zoom in - notice how the outlines don't quite match up**



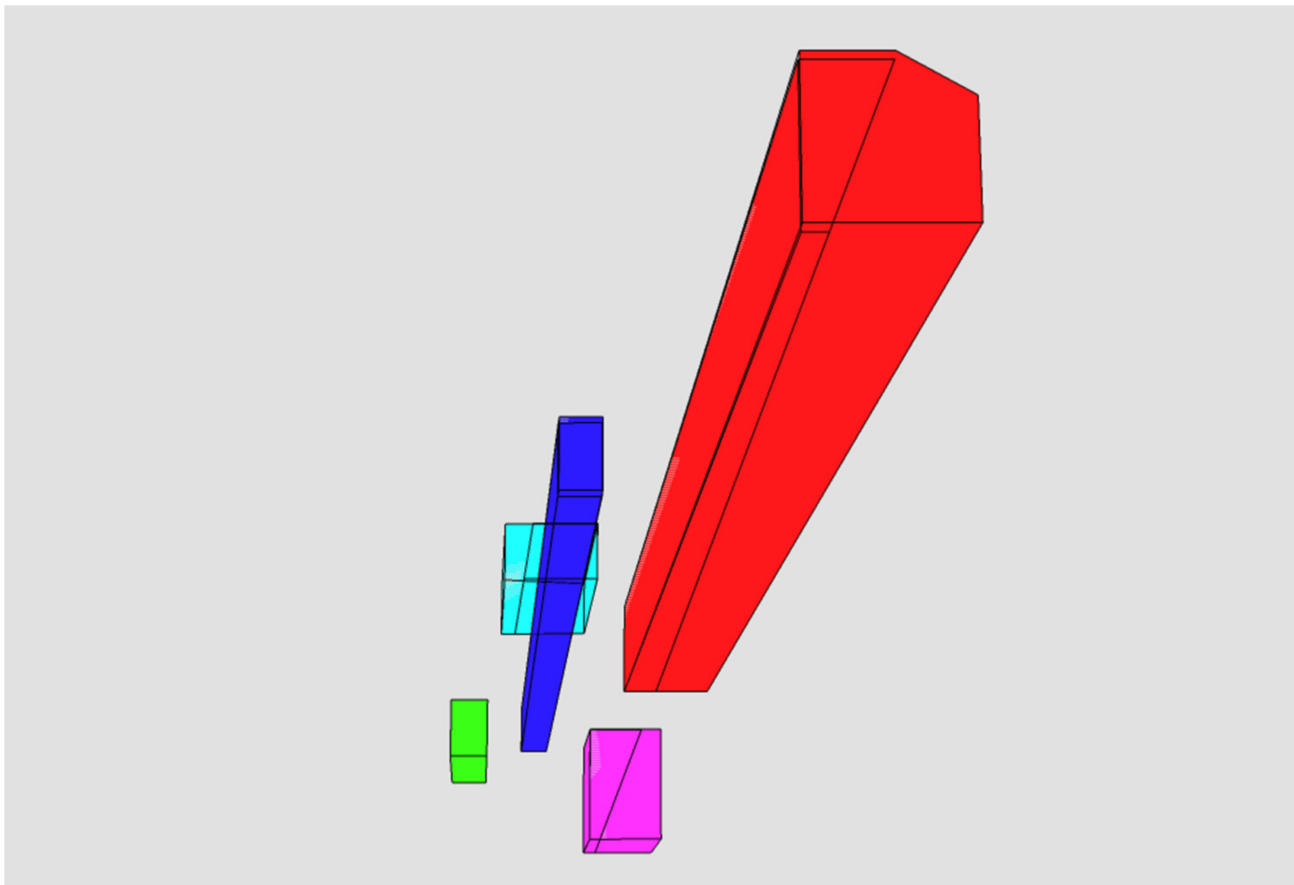
Vertical and Ortho Projections

- **Take the projected result and look at it from above**
  - Some layover but anything on surface is seen undistorted



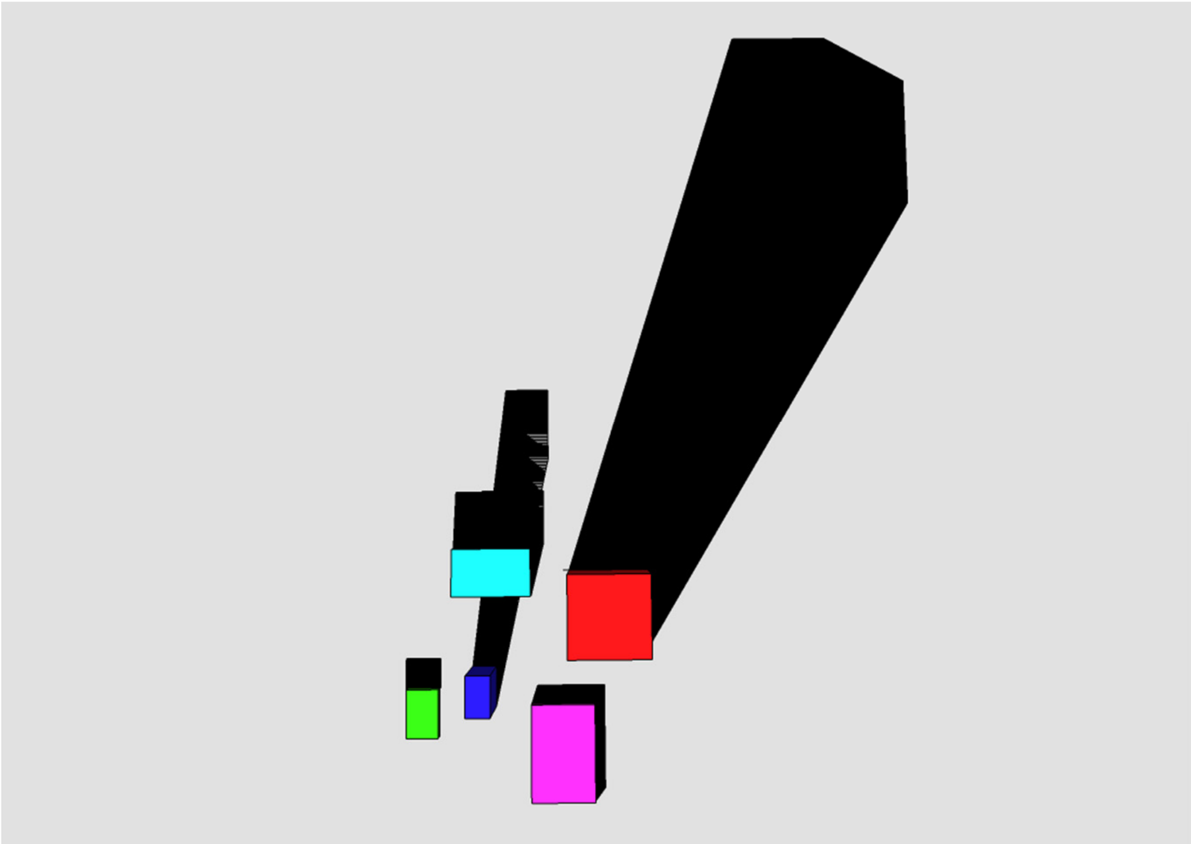
Vertical and Ortho Projections

- **Add tall objects back in**
  - Severe layover and distortion of tall objects



Vertical and Ortho Projections

- **Same scene as an orthorectified mosaic**
  - No distortion, looks like it “should” look from above
  - Gaps result from occlusions



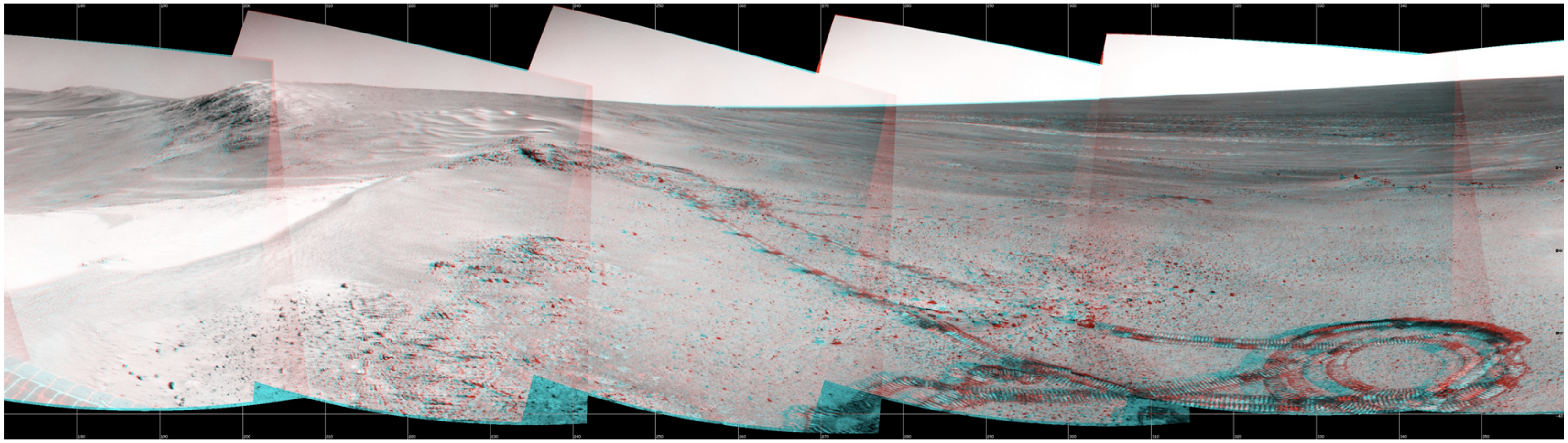
Stereo Mosaics

- **In order to view a mosaic in stereo, separation must be maintained between the left and right eye views**
  - Mosaics must be computed from two different points of view
- **Perspective projection**
  - View as from a single camera
  - Put the camera in two suitable places, and the result can be stereo
  - Only works for a limited fields of view (not panoramas)

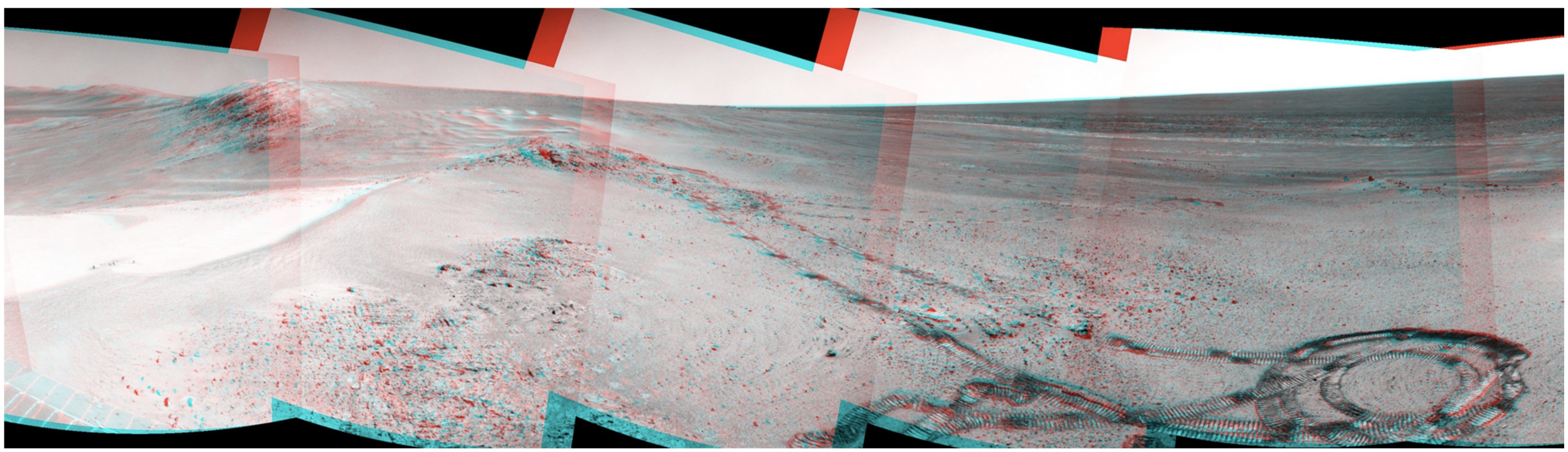
Panoramic stereo

- **Cylindrical projection *cannot be used* for stereo panoramas!**
  - Cylindrical projections stem from a single point of view. Move it over for stereo, and it works ahead and behind but you lose stereo separation to the sides.
  - Simply projecting left and right eye views to the same stereo projection does not give proper depth
    - Result is visually a “wall” with bumps on the wall due to deviations from the surface model. Looks very unnatural.
- **Cylindrical-perspective hybrid projection**
  - Each column of output mosaic is a perspective projection from a different point of view.
  - Point of view describes a circle in space as azimuth changes. This maintains stereo separation between the eyes.
  - Stereo looks natural – flat plane extending to the horizon, with height variations on it.
    - Perfect viewing requires tuning disparity at horizon to viewer’s interocular distance (so it looks to be at infinity)

Cyl vs. cyl-per for stereo



Two cylindrical projections. Foreground appears farther away than horizon over much of the image



Cylindrical-perspective hybrid. Note how stereo depth matches depth cues and expectations

Pointing Correction

- **Geometric seams (discontinuities) are common between images**
  - Parallax
  - Deviations from surface model
  - Imprecise knowledge of camera pointing
- **Seams are minimized via a tiepoint-based bundle adjustment process**
  - Gather tiepoints at overlaps between images
    - Manual or automated process
  - Use bundle adjustment to adjust parameters to minimize tiepoint error
  - Parameters can be:
    - Pointing of individual images (typically az/el of motor joints, could also be XYZ/Euler angles for arm-based cameras)
    - Tilt and location of surface model
    - Localization (pose) of rover if it moved during panorama
      - Rover motion magnifies parallax problems considerably
  - Tiepoint error consists of projecting tiepoint from one image to surface, then back into the second image, and comparing that to where the tiepoint “should” be.

Pointing Correction (cont)

- **Adjusting surface model helps compensate for parallax**
  - Tunes surface model to the particular scene
- **Image pointing adjustment fixes pointing knowledge errors**
  - Also helps with parallax or surface-deviation errors by distributing errors to other seams where they may be less noticeable
  - Pointing adjustments for mast cameras use mast kinematics
    - Represent physically-achievable camera poses
  - Third degree of freedom, “twist” (rotation about camera axis) also often added
    - Helps with minimizing seams
  - Rigid body nature of pointing parameters means (adjusted) camera models still apply, so pixels are traceable to their origin

Brightness correction

- **Variations in brightness or contrast between frames become very visible in a mosaic**
  – Radiometric correction should solve this but is not perfect
- **Brightness correction attempts to match the radiometric seams**
  – Results are no longer radiometrically calibrated, but correction factors are retained so we know what was done to each image
- **Process uses a bundle-adjustment algorithm similar to pointing correction**
  – Gather image brightness/contrast statistics in image overlap areas
  – Adjust brightness/contrast of each image (overall multiplicative and additive factor) to minimize global error in statistical match

Conclusion

- **Mosaics are more complicated than they seem**
  - Parallax
  - Pointing correction
  - Radiometric errors
  - Stereo projection
- **MIPL process has been proven robust and reliable**
- **Questions?**
  - Bob.Deen@jpl.nasa.gov